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Some kinds of pregraphitic carbons exhibit temperature–dependent negative magnetoresistance even at helium temperatures. To account for this anomalous behavior, two assumptions have been introduced. First the sample is composed of an assembly of many thin films which are nearly independent of each other elastically. Secondly, ionized impurity scattering makes an important contribution to the resistivity. Rayleigh waves with small damping and small sound velocity propagate through each film and the scattering due to the Rayleigh wave phonons gives rise to a carrier relaxation rate which decreases as the square of the thin film thickness. Since the screening length of an ionized impurity potential decreases with magnetic field, this process leads to a negative magnetoresistance. Combining these two effects, the qualitative features of the temperature dependent negative magnetoresistance can be explained within the framework of Bright's Theory (Reprint)

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Dr. Don Ulrich	(202) 767-4963	NE NC

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ANOMALOUS TEMPERATURE–DEPENDENT NEGATIVE MAGNETORESISTANCE IN PREGRAPHITIC CARBONS[1]

K. Sugihara and M.S. Dresselhaus

Massachusetts Institute of Technology, Cambridge, MA 02139

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ABSTRACT

Some kinds of pregraphitic carbons exhibit temperature–dependent negative magnetoresistance even at helium temperatures. To account for this anomaly, two assumptions are introduced: i) The sample is composed of an assembly of many thin films which are nearly independent of each other elastically. ii) Ionized impurity scattering makes an important contribution to the resistivity. Rayleigh waves with small damping and small sound velocity ($v_R \sim 10^4$cm/sec) propagate through each film and the scattering due to the Rayleigh wave phonons gives rise to a carrier relaxation rate $1/\tau_p \propto T/d^2$, where d is the film thickness. Since the screening length of an ionized impurity potential decreases with magnetic field, this process leads to a negative magnetoresistance. Combining these two effects, the qualitative features of the T–dependent negative magnetoresistance can be explained within the framework of Bright's Theory.

INTRODUCTION

Some kinds of pyrocarbons and carbon films exhibit temperature–dependent negative magnetoresistance even at T $\simeq$ 1K.[1,2] Figures 1 and 2 illustrate the results for pitch–based carbon fibers.[2] This effect does not seem to be predicted by Bright's model.[3] In this article a mechanism is proposed to account for this effect.

A simple two band model leads to the following expression for $\Delta\rho(H)/\rho(0)$, if $\Delta\rho(H)/\rho(0)$ is sufficiently small:

$$\frac{\Delta\rho(H)}{\rho(0)} \simeq -\frac{\Delta(p+n)}{p(0)+n(0)} - \frac{\Delta\mu(H)}{\mu(0)} + \frac{4p(0)n(0)}{[p(0)+n(0)]^2}\frac{\mu(0)^2H^2}{1+\mu(0)^2H^2} \qquad (1)$$

where p and n indicate hole and electron concentrations, respectively, μ is the mobility, and (0) refers to the zero field value of the parameters. Since the density of states and carrier concentrations increase with H,[3] the first term in Eq. 1 provides a negative contribution to $\Delta\rho/\rho_0$, while the third term represents a positive contribution. Bright's model disregards the second term, but this is important in explaining the T–dependent negative magnetoresistance. We note that $1/\mu$ is composed of several terms:

$$\frac{1}{\mu} = \frac{1}{\mu_b} + \frac{1}{\mu_I} + \frac{1}{\mu_p}, \qquad (2)$$

where $1/\mu_b$ corresponds to the boundary scattering, $1/\mu_I$ to the ionized impurity scattering and $1/\mu_p$ is due to the phonon scattering. Among them, only $1/\mu_I$ is field dependent. The relaxation rate $1/\tau_I$ is related to $1/\mu_I$ and is given by

$$\frac{1}{\tau_I} \simeq \pi N_I g(E_F) \mid v(0) \mid^2 /2\hbar, \qquad (3)$$

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where N_I denotes the ionized impurity concentration, and $v(0)$ is the Fourier component of an ionized impurity potential for $q = 0$. Since the density of states $g(E_F)$ in the weak field region takes the form $a + bH^2$, the Thomas–Fermi approximation yields:

$$\tau_I = 2\hbar g(E_F)/(\pi N_I) \propto a + bH^2. \qquad (4)$$

This indicates that τ_I and μ_I increase with H so that the second term in Eq. 1 also gives rise to a negative magnetoresistance. As will be shown later, the first and second terms in Eq. 1 become

$$\frac{\Delta\rho(H)}{\rho(0)} \simeq -(\alpha\mu(0)^4 + \beta\mu(0)^6)H^2 \qquad (5)$$

under some conditions. Equation 5 would be T–independent at low temperatures if $1/\mu_p$ in Eq. 2 would make a negligible contribution to $1/\mu$, as is the case for most conductors. However, this is not the case for carbon films. To obtain the T–dependence at low T, assume that the sample is composed of an aggregation of many thin films which are weakly coupled with each other elastically. If the film thickness d is small enough ($< 100\text{Å}$), the Rayleigh wave with small damping and small sound velocity scatters carriers even at $T \leq 1$ K, since the typical phonon energies associated with the wave are $\hbar\omega_q/k_0 \sim 1K$. Though $1/\mu_p$ is one or two orders of magnitude smaller than $1/\mu_b$ and $1/\mu_I$, the strong dependence of $\Delta\rho(H)/\rho(0))$ on $\mu(0)$ in Eq. 5 leads to an appreciable T–dependence of $\Delta\rho(H)/\rho(0)$ even at $T \leq 1$ K. Detailed calculations of the on "Electron–Rayleigh Wave Interaction in Thin Film Carbons" are presented in this volume.[4]

TEMPERATURE–DEPENDENT NEGATIVE MAGNETORESISTANCE AT LOW TEMPERATURES

For $E \leq 0.02$ eV, the density of states $g(E, H)$ is approximated by $g(0.H) \simeq a + bH^2$ in the weak field region, where

$$a = \frac{\lambda}{\sqrt{\pi}}\left(N_0 + \frac{2A}{\lambda^2 B}\right), \quad b = \frac{1}{6\sqrt{\pi}}AB\lambda^3,$$
$$A = 4e/(\pi c_0\hbar c), \quad B = \frac{3}{2}(\gamma_0 a_0)^2 e/(\hbar c), \qquad (6)$$

in which c_0 is the interlayer distance and λ^{-1} represents the width of each Landau level. At low temperatures this width is given by $\lambda^{-1} \simeq (\hbar/\tau)/(\ell n2)^{\frac{1}{2}}$.[3] In Eq. 6, N_0 is an excess density of states added to the n = 0 Landau level, and is due to a small 3D–overlap effect. Since we are interested in the negative magnetoresistance, the first two terms in Eq. 1 become

$$\frac{\Delta\rho(H)}{\rho(0)} \simeq -\frac{(\ell n2)^2}{3}\left(\frac{\tau}{\tau_H}\right)^4\left[\frac{1}{1+K} + \frac{1}{2}\left(\frac{\pi^3}{\ell n2}\right)^{\frac{1}{2}}\frac{N_I}{N_0}\frac{K}{(1+K)^2}\right] \qquad (7)$$

where

$$\tau_H = \ell_H/u, \quad \ell_H = (\hbar c/eH)^{\frac{1}{2}}, u = \frac{\sqrt{3}}{2}\gamma_0 a_0/\hbar = 1.02 \times 10^8\text{cm/sec}, \qquad (8)$$
$$K = N_0\lambda^2 B/2A = (\pi\ell n2/4)N_0 c_0(u\tau)^2.$$

i) $K \ll 1$: This is realized for small values of N_0 and μ, for example $N_0 \simeq 10^{18}\text{cm}^{-3}$ and $\mu \simeq 0.1m^2/Vs$.

In this case we have $\Delta\rho(H)/\rho(0) \simeq -[\alpha\mu(0)^4+\beta\mu(0)^6]H^2$, which is the result given by Eq. 5. Though $\alpha\mu^4$ is comparable to $\beta\mu^6$, they have different temperature dependences. Namely,

$$\mu(0)^4=\mu_0^4/(1+\varepsilon)^4, \quad \mu(0)^6 = \mu_0^6/(1+\varepsilon)^6, \quad \varepsilon = \mu_0/\mu_p = \tau_0/\tau_p,$$
$$1/\tau_0 = 1/\tau_b + 1/\tau_I, \quad 1/\tau_p \propto L_a T/(v_R d)^2, \tag{9}$$

where L_a is the crystallite size in the xy–plane and $v_R \sim 10^4$ cm/sec. Though ε is small $(10^{-1} \sim 10^{-2})$, the strong dependence on μ leads to an appreciable T–dependence of $\Delta\rho(H)/\rho(0)$ which is consistent with the observed results (see Figs. 1 and 2 where $L_a \sim 110$ Å and $d < 100$ Å are assumed).

ii) K >> 1: In this case $\Delta\rho(H)/\rho(0)$ becomes

$$\frac{\Delta\rho(H)}{\rho(0)} \simeq -\frac{(u\tau)^2}{N_0 c_0}\left(\frac{eH}{\hbar c}\right)^2\left(0.29 + 0.98\frac{N_I}{N_0}\right) \propto \frac{\mu^2 H^2}{(1+\varepsilon)^2}. \tag{10}$$

This gives a weaker T–dependence than that of Eq. 5.

References

[1] P. Delhaes, P. de Kepper and M. Uhlrich, *Philos. Mag.* 29, 1301 (1974).

[2] P.D. Hambourger, *App. Phys. Commun.* 5, 223 (1985–1986); P.D. Hambourger and R.A. Boyer, *Bull. Am. Phys. Soc.* 31, 643 (1986).

[3] A.A. Bright, *Phys. Rev.* B20, 5142 (1979).
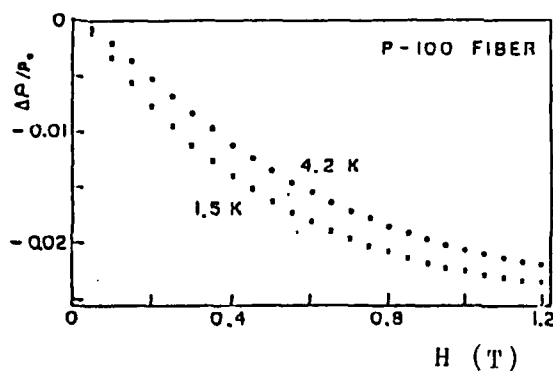
[4] K. Sugihara, *this volume.*

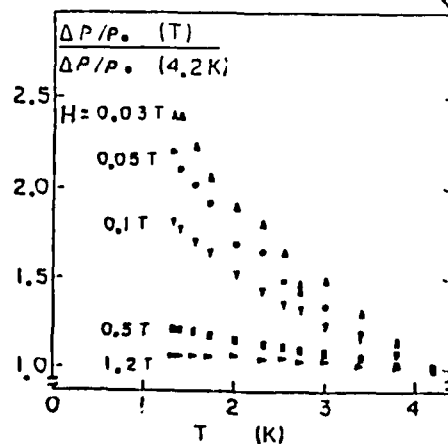Figure 1: Magnetoresistance *vs.* magnetic field strength (H) for pitch–based fibers.[2]

Figure 2: Magnetoresistance (normalized to 4.2 K) vs temperature for several field strengths for pitch–based fibers.[2]

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